7.4 Evaluating the Effects of Emission Reductions on Multiple Pollutants Simultaneously

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Abstract Modeling studies over the Philadelphia metropolitan area have examined how emission control strategies might affect several types of air pollutants simultaneously. NOx reductions in July are predicted to increase ozone in the urban core and decrease it elsewhere, decrease $PM_{2.5}$ and formaldehyde, and slightly increase acetaldehyde and 1,3-butadiene. In January, NOx reductions increase ozone, formaldehyde and acetaldehyde everywhere. VOC reductions decrease aldehydes but have little effect on ozone in this domain. A combination of VOC and NOx reductions reflects the cumulative behavior of each of the emission reductions separately, and minimizes disbenefits for both HAPs and ozone. A comparison of these changes in terms of their effect on health shows that differing behavior of $PM_{2.5}$ and ozone can counterbalance each other to some extent. While changes in HAPs are affected by changes to reduce ozone and $PM_{2.5}$, their effect on health impacts is smaller than $PM_{2.5}$ and ozone. This study supports considering effects of multiple pollutants in determining optimum pollution control strategies.

Keywords Emission control, HAPs, multipollutant, ozone

1. Introduction

Many areas around the world have air quality problems with simultaneously high concentrations of one or more pollutants, including ozone (O_3), particulate matter ($PM_{2.5}$), oxides of nitrogen (NOx) and/or hazardous air pollutants (HAPs). There is a growing awareness that pollution control should be considered for its overall benefit to pollutants, rather than on a single pollutant basis (Scheffe et al., 2007). There has been some discussion on the potential effect of volatile organic hydrocarbon (VOCs) and NOx control on species other than ozone, such as other oxygenated nitrogen species and secondary organic aerosol (National Research Council, 1991; Russell et al., 1988; Blanchard et al., 2007), but few comprehensive, multi-pollutant studies, especially considering effects on HAPs. Ozone and the secondarily-produced portion of $PM_{2.5}$ and HAPs are interrelated through complex atmospheric photochemistry, so control strategies for $PM_{2.5}$ and ozone might

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decrease or increase HAP concentrations. There are ongoing efforts to reduce concentrations of important pollutants to meet health standards for ozone, NOx and particles, but these reductions will affect the concentrations of radicals and VOCs that produce and destroy HAPs. We need to understand the effect of these controls on HAP concentrations in order to calculate the full economic benefit of control strategies or compare alternative strategies.

In this study, we use a three-dimensional air quality model, the Community Multi-Scale Air Quality (CMAQ) modeling system, to examine the effect of emission control strategies on concentrations of ozone, $PM_{2.5}$, and four important HAPs: formaldehyde, acetaldehyde, 1,3-butadiene and benzene. The objective of this paper is to begin to address the question of how control strategies formulated for pollutants such as ozone and PM might benefit or disbenefit other pollutants.

2. Model Formulation and Application

Model simulations are centered on the Philadelphia metropolitan area, with a 4-km horizontal grid size, (76 by 82 cells), and 15 vertical layers, nested within a continental-scale simulation with a 36-km horizontal grid resolution (Figure 1). We used CMAQ v4.5 (Byun and Schere, 2003; Community Modeling and Analysis System, 2006). Within this domain, we selected four grids representing different chemical characteristics, noted as A, B, C and D. Grid A is located in urban central Philadelphia, B is upwind of the urban area, C and D are on the same latitude as A, but more rural. Emissions for 1999 were used, with a refined mobile source inventory for Philadelphia. The MM5 v3.6.1 model provided meteorological fields (MM5 Community Model, 2007). We performed base case model simulations for January and July, 2001. The SAPRC-99 chemical mechanism (Carter, 1990), modified to include 26 explicit air toxics (Luecken et al., 2006) characterizes the chemistry.

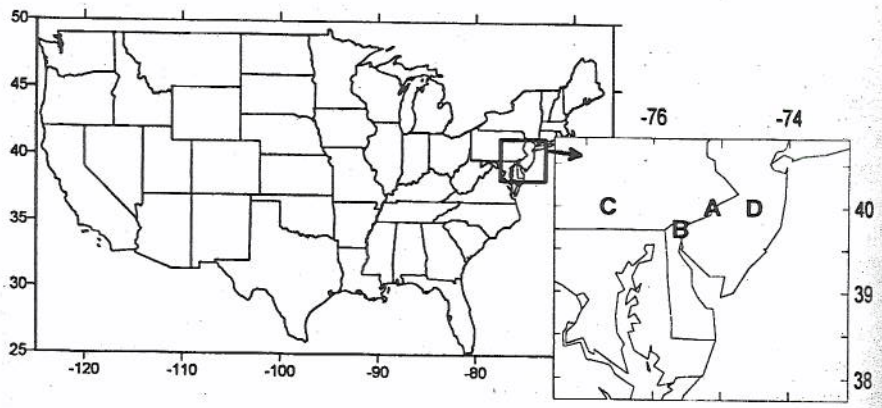

Fig. 1 Simulation domain with nested area and location of grid cells for detailed analysis

To examine how pollutant concentrations might be affected differently by emission reductions, we performed sensitivity studies with across-the-board anthropogenic emission reductions. The studies simulated two periods, July 14–25, 2001 and January 10–21, 2001. While these reductions do not reflect "realistic" control scenarios, they mimic potential future emission reductions. The three scenarios are (1) 50% reduction in nitric oxide and nitrogen dioxide emissions (NOx-only); (2) 20% reduction in VOC emissions (VOC-only); and (3) 50% reduction in NOx and 20% VOC reduction in VOC emissions (NOx + VOC). Biogenic emissions constitute a significant portion of VOC emissions, so the overall cut in the VOC-only scenario is less than 20%. To account for reduction of pollutant transport, we reduced NOx and VOCs at the boundaries by 50% or 20% of the anthropogenic portion. We compare strategies at the four different grid points shown in Figure 1.

3. Results

3.1. Concentrations

Changes in ozone and $PM_{2.5}$ for the July simulation are shown in Figure 2. Ozone values are 12-day averages of the daily maximum 8-hour average concentrations, and $PM_{2.5}$ values are calculated as 12-day averages. This domain has an urban corridor (represented by grid A) that is largely VOC-sensitive but surrounding areas that are NOx-sensitive. Ozone in the urban corridor is predicted to increase when NOx is reduced, while other grids show ozone decreases in the NOx-only scenario in July. The VOC-only scenario has a small effect on decreasing ozone, and the NOx +VOC simulations show larger benefit and less disbenefit than the NOx-only simulations.

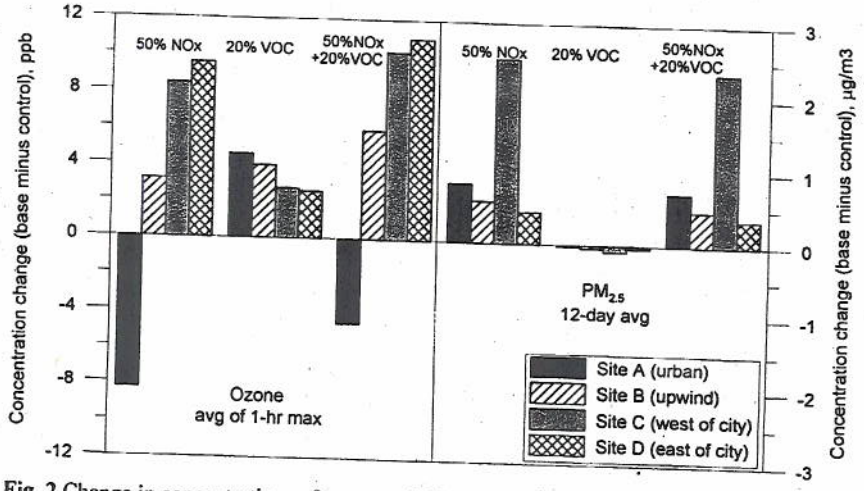

Fig. 2 Change in concentrations of ozone and PM2.5 for each sensitivity scenario during July

The NOx-only reductions have a small effect on the $PM_{2.5}$ concentrations (4–12% reductions) due to decrease in formation of aerosol nitrate. Nitrate comprises a small portion of the total $PM_{2.5}$ (1–17%) and we predict the largest $PM_{2.5}$ decreases where the fraction of nitrate in $PM_{2.5}$ is largest (grid C, where ammonia emissions are large) and the smallest effect in grid D, where nitrate is low. There is a small change in $PM_{2.5}$ because changes in ozone and OH affect formation of organic aerosol (increases at grid A, decreases elsewhere) and aerosol sulfate. For the January episode, the ozone increases in the NOx-only scenario for all grids, slightly less so in the VOC + NOx scenario. The $PM_{2.5}$ changes are less than 0.5%.

Figure 3 shows changes in the 12-day average concentrations of formaldehyde, acetaldehyde, 1,3-butadiene and benzene for each of the emission reduction scenarios, calculated as (base – control). Formaldehyde concentrations are reduced by a small amount and acetaldehyde concentrations are increased on average when NOx emissions are reduced, but the variability of the data is also large. The 1,3-butadiene increases in C and D and decreases in A and B. The aldehydes are primarily produced in the atmosphere from other VOCs, so changes in ozone, OH, hydroperoxy radical and organic radicals resulting from emission cuts affect concentrations of formaldehyde and acetaldehyde in a complex manner. Although all four HAPs that we examine are VOCs, the concentrations of aldehydes do not change linearly with the VOC reductions. Benzene, on the other hand, shows an approximately linear reduction with VOC emission reductions. In January, both formaldehyde and acetaldehyde increase with the NOx-only scenario but decrease in all others, benzene has negligible change, and 1,3-butadiene decreases for all.

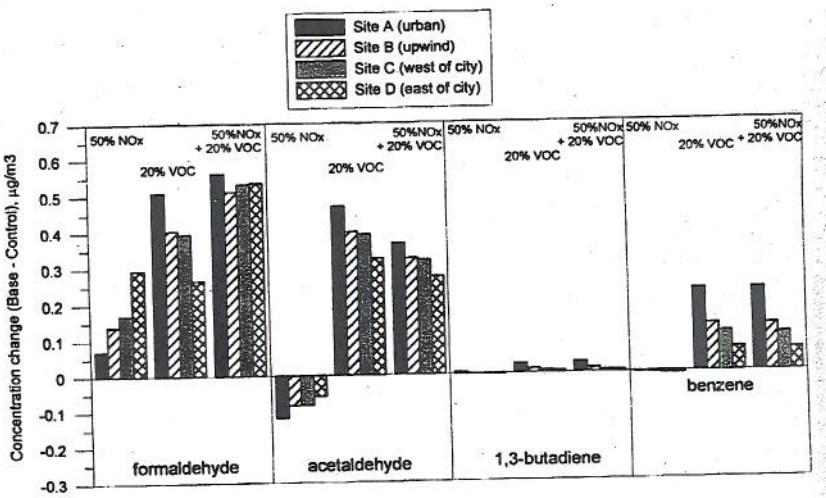

Fig. 3 Change in concentrations of four HAPs for each sensitivity scenarios during July

3.2. Comparison of changes in terms of health days lost

Differing responses to pollutant reductions by ozone, $PM_{2.5}$ and HAPs make it difficult to determine an overall, optimum control strategy. What types of strategies should be pursued if a strategy increases some pollutants but decreases others? To compare relative changes for different types of pollutants, we attempt to normalize them by converting into health-related effects.

There are several different ways to characterize health effects. Exposure modeling, as described in Georgopoulos et al. (2005), provides one of the most accepted and complete ways to estimate overall health effects by accounting for indoor and outdoor pollutant sources, movement of people, local peaks, etc. While these models are appropriate for small-scale studies with finely-resolved concentration gradients, they are more difficult to apply and require fine-scale inputs.

Another option for estimating changes in health endpoints is concentration-response functions derived from relationships between ambient concentrations and health effects (US EPA, 1999). These are useful for analyzing regional-scale control strategies where only ambient sources are controlled. Because the goal of this study is to estimate relative changes in $PM_{2.5}$, ozone and HAP concentrations, we use concentration-response functions to quantify the direction and approximate changes in health effects due to changes in each pollutant. While not as comprehensive as exposure models, the results can screen potential control scenarios which can be followed up with more detailed exposure modeling. To include effects in both summer and winter, we summed January and July responses.

For ozone and $PM_{2.5}$, we follow the method used for ozone by Tong et al. (2006). Short-term mortality, hospital admissions, and ER visits for respiratory conditions were included for ozone. For $PM_{2.5}$, long-term mortality for adults 30 years and older was included. For ozone and $PM_{2.5}$ concentration changes, ΔC_i, we calculate change in the base rates of each health endpoint, ΔH_i, using a log-linear equation:

$$\Delta H_i = \left[\exp\left(\beta_i * \Delta C_i\right)\right] \tag{1}$$

where $\beta = 0.00052$ for daily ozone short-term mortality (Bell et al., 2006), $\beta = 0.00631$ for hospital visits (Burnett et al., 2001), and $\beta = 0.0035$ for emergency room visits for asthma (Stieb et al., 1996). For $PM_{2.5}$, we use $\beta = 0.006$ for annually-averaged $PM_{2.5}$ (Pope et al., 2002) for adults older than 30 years. We use a 25 ppb threshold value for ozone, and no threshold for $PM_{2.5}$. We report the total value in terms of change in health days, HD_i from the base rate for each population age group and the days lost for each mortality, D_m, with a median lifetime of 77 years:

$$HD_i = H_{base,i} * \left(\Delta H_i - 1\right) * population * D_m \tag{2}$$

There is not a consensus on how to compare health effects from HAPs with those from ozone and $PM_{2.5}$ because the health effects differ. For HAPs examined in this

study, carcinogenic effects are of most concern. To calculate health days lost due to mortality from carcinogenic effects of HAPs, we use linear equations of the form

$$\Delta H_i = \beta_i * \Delta C_i / 70 \quad (3)$$

$$HD_i = \Delta H_i * population * D_m * 0.44 \quad (4)$$

Values of β are Unit Risk Estimates reported in the US EPA Integrated Risk System (US EPA, 2007), with β = 1.3E-5 for formaldehyde, β = 2.2E-6 for acetaldehyde, β = 3.0E-5 for 1,3-butadiene and β = 5.0E-6 for benzene. The changes in health days are based on a 70 year lifetime, consistent with National Air Toxic Assessment (US EPA, 2006), a 44% fatality rate for all cancers (American Cancer Society, 2001) and the base mortality distribution.

Figure 4 shows the overall change in health days for each scenario at the four grids for ozone, $PM_{2.5}$, the sum of HAPs and the overall sum. At some grids for some scenarios, the PM2.5 and ozone have opposite effects on health days, and the overall sum reflects those counteracting effects. The HAPs examined in this study show small contributions to the changes in health days. Because only four out of hundreds of recognized HAPs were included in this analysis, the total effects of all HAPs, especially with other high risk HAPs such as diesel PM and acrolein, would be larger than the values displayed here. Since some HAPs decrease under the NOx-controlled scenarios and some increase, the health effects balance out somewhat when computing the sum of effects from HAPs.

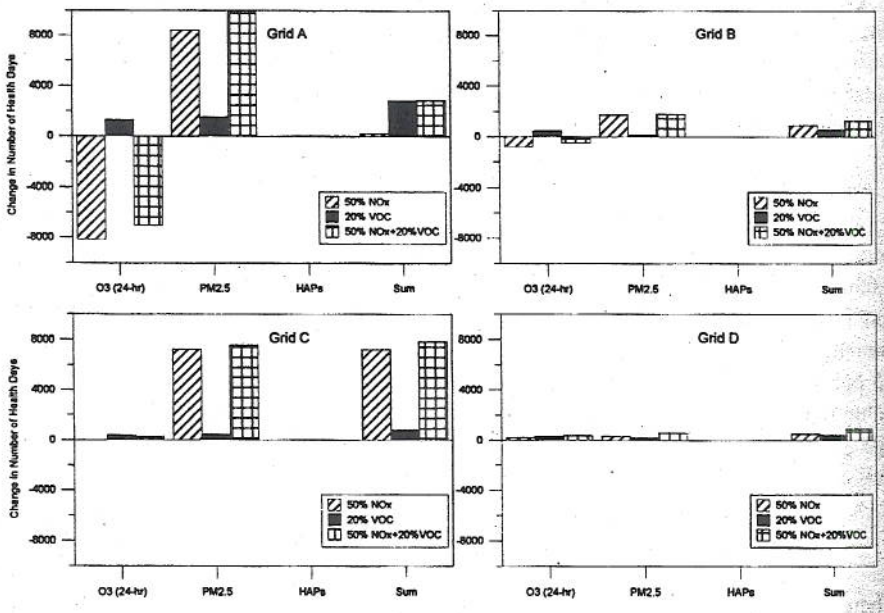

Fig. 4 Change in number of health days for three emission change scenarios at four grids

4. Summary and Conclusion

Modeling studies over the Philadelphia metropolitan area have examined the potential for emission control strategies to affect several types of air pollutants simultaneously, through both direct and indirect effects of emission reductions. Over this domain, a 50% NOx reduction in July increase ozones in the urban core and decreases ozone elsewhere, decreases $PM_{2.5}$ and formaldehyde, and slightly increases acetaldehyde. In January, NOx-only reductions increase ozone, formaldehyde and acetaldehyde everywhere, to a significant fractional extent. When considering VOC-only reductions, we predict that a 20% reduction in VOCs decreases aldehyde concentrations everywhere, although the decreases are less than 20%, but has little effect on ozone in this domain. A combination of VOC and NOx reductions reflects the cumulative behavior of each of the emission reductions separately, and minimizes disbenefits for both HAPs and ozone.

Comparing these changes in terms of their effect on health allows us to initially rank emissions change scenarios and to compare different scenarios in terms of their overall potential effect on health. The differing behavior of species supports the need to consider effects of multiple pollutants in determining optimum pollution control strategies. While changes in HAPs, including secondarily-produced ones, are affected by changes to reduce ozone and $PM_{2.5}$, their effect on health impacts is smaller than $PM_{2.5}$ and ozone. We note that uncertainties in concentration-response functions, in HAPs risk estimates, and in base rates of mortality could change the conclusions, and future work should be done to explore the effect of these uncertainties on the identification of optimum control strategies.

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Discussion

S.T. Rao:

In addition to the concentration-response functions, are you looking at the exposure-response functions is assessing the impact of emission reduction strategies?

D. Luecken:

We have used concentration-response functions to perform our initial analyses because we are looking at relative changes in health effects. However, our plans for follow-up work on the next project include using exposure modelling as a more detailed way to compare overall health impacts in the Baltimore, MD area.